Grid Influences From Reactive Power Flow of Photovoltaic Inverters With a Power Factor Specification of One

Andreas Spring, Georg Wirth, Gerd Becker, Robert Pardatscher, and Rolf Witzmann

***Abstract*—This paper discusses the influence of unintended reactive power flow caused by photovoltaic (PV) inverter systems with a power factor specification of one on the grid voltage and grid loss. In theory, the apparent power feed-in of these PV systems should be equal to the active power feed-in. Observations in distribution grids have shown a reactive power flow caused by these systems. The main purpose is, if this influence has to be considered in grid planning and power system management in smart grids. Therefore, measurement data of several low voltage grids is used. Three different scenarios for the unintended reactive power are simulated. Under normal operating conditions, the unintended reactive power is not relevant. Nevertheless, if voltage or overload problems are not explainable, they can be a result of the unintended reactive power flow. This approach is very helpful for network operators to locate and understand the reasons for grid problems.**

***Index Terms*—Distributed power generation, inverters, photovoltaic (PV) systems, power system measurements, power system reliability, reactive power, smart grids, solar power generation, voltage control.**

I. Introduction

IN 2013, photovoltaic (PV) systems in Germany produced 29.7 TWh, corresponding to 5.2% of the German electricity demand [1]. Approximately 80% of these PV systems are connected to the low voltage grid [2]. The feed-in is decentralized and inverters with numerous power electronics—instead of synchronous generators—are used. Due to this high PV penetration, new challenges arise for guaranteeing the required network stability and power quality.

The massive buildup leads to unknown grid conditions, especially in the low and medium voltage level and quite high feed-in powers and reverse power flows occur. In some rural areas, the feed-in power temporarily exceeds the local load and has, therefore, become the decisive factor in network planning [3]. Hence, the distribution grid operators have to strengthen the grid to absorb the high feed-in capacities. Furthermore, high power feedback occurs from the low voltage to medium and even high voltage level, as well as lifted voltages at feeders with low short circuit powers.

These voltage deviations have to stay within the normative boarders of the DIN EN 50160 [4] of $\pm 10\%$ of the rated grid voltage. The deviations also have to fulfill the German application guideline VDE-AR-N 4105 [5] that permit a maximum voltage rise due to the sum of all distributed generations of 3% in low voltage grids.

The results obtained in this paper originate from the investigations of the research project "Grid of the Future" [3]. The aim of this paper is the understanding of the impact of a high number of renewable energy systems on the distribution network, and the new conditions that arise due to the high number of renewable energy systems. The project area includes one medium voltage grid and the underlying low voltage grids with an installed average PV capacity of more than 5.0 kW per house connection (HC) [6]. Smart meters record the active and reactive power of approximately 320 PV systems.

The primary question of this paper is, if the influence of unintended reactive power flow has to be considered in grid planning and power system management in smart grids. The analysis of the possibilities to prevent the unintended reactive power flow is not the essential purpose.

A. Fundamentals

All active, reactive, and apparent power flows in this paper refer to the 50-Hz component. The reactive power distortion of inverters with a power factor specification of one can be neglected. This shows a comparison between the 50-Hz component and total reactive power. The differences between the 50-Hz component and total reactive power flow are lower than 5 VAr. Therefore, the power factor regarding [7] is identical to the power factor of the fundamental wave and the displacement factor. In the following discussion, the term "power factor" ($= \cos\varphi$) is used. In this paper, unintended reactive power means an exchange of reactive power between the grid and inverters with a power factor specification of one ($\cos\varphi = 1$). The analyzed inverters have no dynamic volt ampere reactive compensators as described in [8]–[10]. All inverters are commercially available for rooftop applications. The reasons for the unintended reactive power flow are the Combination of inductor/capacitor/inductor (LCL) grid filters of the installed inverters. On the input side of these filters (equal to the output

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side of the bridge) no reactive power flow occurs. Depending on the current through the filter a reactive power flow originates. Consequently, the power factor on the grid connection point is no longer one.

To prove the accuracy of the smart meters (EMH LZQJ-XC) that are installed for the measurements in the research project Grid of the Future various PV inverters with a power factor specification of one are analyzed in the laboratory with different power quality analyzers (PQ-Box 200 and Fluke PQ-Analyzer 1760). The obtained results confirm the field measurements. Furthermore, the same smart meters that measure the PV power in the research project are used for load measurement. In these measurements no unintended and unexplainable reactive power flows appear.

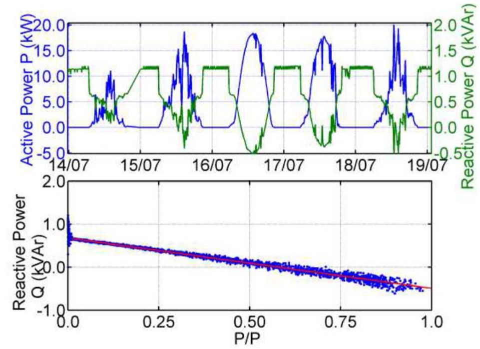

Fig. 1. Dependency of the reactive power on the active power for one inverter. Negative reactive power represents an inductive consumer.

B. Structure

This paper is organized as follows. Section II describes the unintended measured reactive power flow of various PV inverters with a power factor specification of one. In Section III, the influence of these reactive power flow on the grid voltage and the power loss in the grid is simulated. Therefore, Sections III-A–III-C explain the basics of the simulation, influence on the voltage, and influence on the power loss, respectively. The results of this paper and the conclusion are given in Sections IV and V.

II. Comparison of the Unintended Reactive Power Flow of Inverters

A field measurement survey of various PV inverters with a fixed power factor specification of one was carried out. Despite the power factor specification, all investigated inverters do have a reactive power flow. High deviations of the power factor from the specification occur, especially in the part load range. Dependency of the reactive power on the stage of utilization and, therefore, the amplitude of the irradiation can be observed. Deeper part load operation, respectively lower irradiation values, mostly lead to higher reactive power flows. Most of the unintended reactive power flows show a linear dependence on the active power. Therefore, a reactive power best-fit line for each inverter can be developed. The upper part of Fig. 1 shows the active and reactive power flow of one inverter for five days. A positive reactive power flow represents a capacitive consumer; negative reactive power flow is equal to an inductive consumer. During the night, the LCL filter produces a capacitive power flow; during a high feed-in an inductive power flow occurs. The lower part of Fig. 1 expresses the dependency of the reactive power on the active power. The blue points are real measurement values in a 10-min interval for one month. These points can be approximated by a reactive power best-fit polynomial of the first degree (red line). The reason for that behavior is the dependency of the reactive power on the injected current. The higher the feed-in current the higher is the influence of the inductive part of the LCL grid filter.

To compare the unintended reactive power flow of all inverters which are measured in the research project Grid of the Future [11], each inverter is allocated a reactive power best-fit polynomial of the first degree. In the following discussion, the comparison of the reactive power flow of all measured PV inverter systems for three low voltage grids will be presented.

For each inverter, the reactive power best-fit line for the day with the highest active power feed-in in 2011 is compiled (May 9, 2011). The power flow of this day leads to the most severe burden of the networks. Figs. 2–4 communicate these polynomials in dependency of the gradient and reactive power at no active power feed-in (y-intercept) (left part), as well as in dependency of the gradient and reactive power in full load operation (right part) for three different low voltage grids. The size of the marker represents the quotient of the reactive power in full load operation of each specified inverter (dividend) and the sum of all reactive powers in full load operation (divisor) (left), as well as the maximum reactive power flow of the specified inverter (right). Positive values are capacitive (overexcited); negative values are inductive (underexcited). Inverters with an absolute maximum reactive power (independent of the stage of utilization) in the capacitive range are described by circles; in the inductive range a rectangle is used. This maximum reactive power flow can occur in deep part load operation or in full load operation.

The reason for the axis representation is the easy way to understand the inverter behavior. A positive reactive power at no active power feed-in (positive values in the left plot), an additional negative gradient and a negative value in full load operation represents a grid voltage stabilization behavior. In comparison, destabilize negative reactive power values at no active feed-in or positive reactive power values in full load operation the grid voltage.

Fig. 2 displays a small low voltage grid (114 HC and maximum load 283.5 kW) with seven measured PV systems. The mean reactive power of all seven systems is inductive and amounts to 339 VAr. There is one 20 kW system with 4.4 kVAr inductive reactive power in near full load operation. The quotient of the reactive power in full load operation and the sum of all reactive powers in full load operation varies between 1.32% and 58.3% for the seven inverters with an average of 14.3%. Once again, all analyzed inverters in this paper do have a power factor specification of one.

The low voltage grid in Fig. 3 (630 HC and maximum load 1764 kW) shows one 10 kW inverter with an inductive reactive

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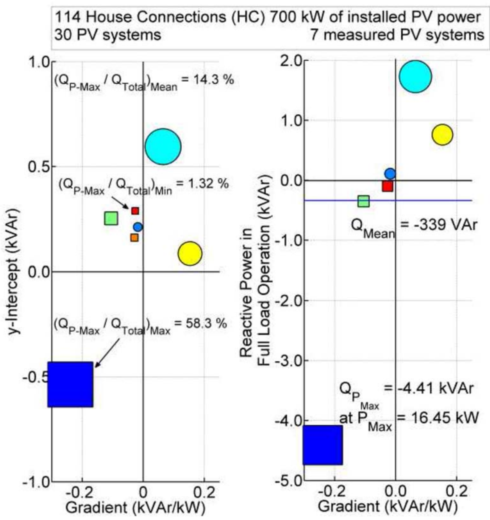

Fig. 2. Comparison of diverse inverter types for the day with the highest active power feed-in for one small low voltage grid with 114 HCs.

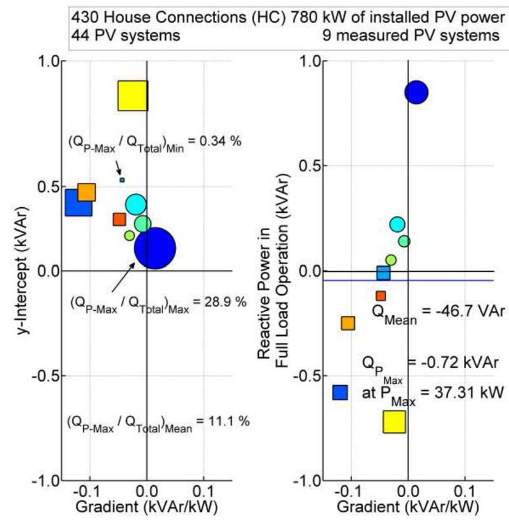

Fig. 4. Comparison of diverse inverter types for the day with the highest active power feed-in for a third low voltage grid with 430 HCs.

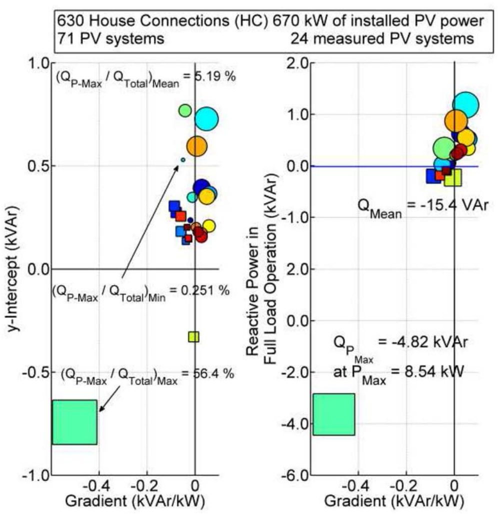

Fig. 3. Comparison of diverse inverter types for the day with the highest active power feed-in for a low voltage grid with 630 HCs.

power flow of 4.8 kVAr in near full load operation. This power is equal to more than 50% of the unintended reactive power due to PV systems. All other PV inverters evoke much smaller reactive power flows.

Fig. 4 displays another low voltage grid (430 HC and maximum load 491 kW). The mean value of all unintended reactive power flow sums to 46.7 VAr inductive. The highest inductive reactive power flow in full load operation amounts to 0.7 kVAr during an active power feed-in of more than 37 kW. The maximum share of the reactive power in full load operation of one single inverter is 28.9%; the minimum is 0.34%.

All three example low voltage grids have an inductive medium reactive power flow in full load operation. This means the grid voltage should be decreased due to the unintended reactive power flow. On the other hand, there are some inverters that feed-in inductive reactive power in full load operation and boost the grid voltage. Hence, there must be areas in the grid with increased voltages and areas with decreased grid voltages due to the unintended reactive feed-in.

The markers of one inverter for all days are close together for the majority of inverters. These markers represent inverters with a strongly pronounced proportionality. With divergence of the markers, the proportionality is not solidly pronounced. Most inverters (90%) confirm the linear dependency quite well. The maximum reactive power flow ranges up to 5 kVAr inductive and 2 kVAr capacitive. This is mostly the case for PV systems in the double-digit kilowatt range. Inverters below 10 kW (installed nominated inverter powers: 1.8–9.5 kW) show a much smaller reactive power flow.

III. Influence of the Unintended Reactive Power Flow on Grid Voltage and Power Loss

In this section, simulated calculations on the influence of the unintended reactive power flow of PV inverters on grid voltage and power loss in the cables and transformers is carried out. The simulation is done in low voltage grids with a high PV penetration.

PV inverters with a power factor specification of one contribute to reactive power flow in the grids. All power flows have an impact on grid voltage. The most interesting scenario is the full load operation. In distribution grids with a high PV penetration, the voltage at long feeders with PV is enhanced. An additional unintended capacitive behavior (consumer reference arrow system) leads to even higher voltages that reach a critical range. In comparison, an unintended inductive behavior in full load operation leads to a voltage reducing effect that mitigates the voltage problems.

The loss in grid power is proportional to the square of the absolute current and, therefore, increases with escalating reactive power flow. Consequently, power loss is independent of the direction of the reactive power, but depends on the absolute value of the power. In low voltage grids with an inductive behavior, because of the loads, the reactive power flow and, therefore, the loss is reduced by a capacitive reactive power

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flow (reactive power compensation). This is especially the case during a deep part load operation of the inverters.

A. Basics of the Simulation

In the following discussion, the variation in grid voltage and grid power loss in the three low voltage grids (nominal voltage $-V_n = 0.4$ kV), introduced in Section II, during full load operation (voltage) and during one year of investigation (losses) with and without the unintended reactive power flow will be presented. For the voltage simulation, the active and reactive power flow of the day with the highest active feed-ins in 2011 is chosen (May 9, 2011). This is the most critical situation for the low-voltage grids. For the grid loss simulation, the whole year 2011 is analyzed.

1) Measured PV Systems: The input parameters of the simulation are the active and reactive power flow of all measured PV systems in the selected low voltage grid in a 10-min interval. The total capacities of all PV systems in the three low voltage grids amount to 700/670/780 kW distributed on 30/71/44 PV systems. The input data is available for 7/24/9 PV systems. For these systems, the real measured powers are deposited into the network simulation tool PSS SINCAL [12]. In this tool, a PV system is modeled by using the load flow type "*P* and *Q*." Therefore, only the active and reactive powers are used. A diurnal variation is deposited in a databank. The calculation is carried out via a Newton–Raphson iteration procedure.

2) Nonmeasured PV Systems: A normalized average value for the active feed-in for one whole day is calculated from the measured active power. This normalized profile multiplied by the rated power of the remaining PV systems is the active power input data of all nonmeasured PV systems. The reactive power of the nonmeasured PV systems ($Q_{\text{non-mea}}(t)$) is calculated in three different ways.

1) The first calculation method (C1—mean) is an average reactive power out of all n (n = number of measured PV systems in one low voltage grid) measured reactive power flow ($Q_{\text{mea}}(t)$)

$$Q_{\text{non-mea}}(t) = \frac{\sum_{i=1}^{n} Q_{i,\text{mea}}(t)}{n}. \tag{1}$$

2) In the second calculation (C2—ind) the course of the PV system with the maximum inductive power flow ($Q_{\text{ind,max}}(t)$) is divided by the rated active power P_r of this system. This course is then multiplied by the rated power of the nonmeasured systems $P_{r,\text{non-mea}}$ and finally the specific system assigned

$$Q_{\text{ind,max}}(t) = \text{Maximum}(Q_{\text{ind}}(t)) \tag{2}$$

$$Q_{\text{non-mea}}(t) = \frac{Q_{\text{ind,max}}(t)}{P_r} * P_{r,\text{non-mea}}. \tag{3}$$

3) The third way (C3—cap) is similar to the second by using the maximum capacitive power

$$Q_{\text{cap,max}}(t) = \text{Maximum}(Q_{\text{cap}}(t)) \tag{4}$$

$$Q_{\text{non-mea}}(t) = \frac{Q_{\text{cap,max}}(t)}{P_r} * P_{r,\text{non-mea}}. \tag{5}$$

Inverters with lower rated powers can produce higher reactive power flows. Normally, PV inverters with a higher rated power produce higher reactive power flows. The calculation by methods 2) and 3) take this correlation into account and are worst case simulations.

3) Analyzed Low Voltage Grids: The structure and parameters of the simulated low voltage grids are known and available in the network simulation tool. The low voltage grids are located in rural areas with a large percentage of household and agricultural loads and only a few industrial loads. There are a lot of weak and long power lines, especially to farms that are located a bit outside of the villages. This leads to low short circuit powers and high voltage rises/falls on the load-dependent impedance of the cables. Additionally, the farms do have a large PV built-up capacity because of their extra-large roof surface area. The installed cables do have a line resistance between 0.206 and 0.641 (Ω/km), the reactance is in the range of 0.080–0.085 (Ω/km). The capacitive line coverings are neglected. All simulations and calculations are done with and without the unintended reactive power flow of PV inverters with a power factor specification of one for each of the three low voltage grids. The low voltage grids are connected to the overlaid medium voltage grid. All connections between this medium voltage grid and other low voltage grids have a constant load and supply and, therefore, no day-courses in the power flow. The loads in the analyzed low voltage grid are chosen for a low-load scenario [13] and are constant over the whole investigation period.

B. Influences on the Grid Voltage

In this section, the influence of the unintended reactive power flow on the grid voltage in three exemplary low voltage grids is analyzed. Figs. 5–7 display the results of the grid voltage on all grid nodes in the low voltage grids with and without the unintended reactive power for the timestamp with the highest active power feed-in for the calculation method C1—mean. Therefore, the difference between the two calculations is exposed. The color bar displays the relative voltage change (Δv_{rel}) in percent (%) according to (6). Therefore, the voltages $v_{\text{with }Q}$ and $v_{\text{without }Q}$ are relative voltages based on the nominal voltage (400 V) and given in percent (%)

$$\Delta v_{\text{rel}} = v_{\text{with }Q} - v_{\text{without }Q}. \tag{6}$$

The voltage is calculated on each grid node (black points) and interpolated over the complete area of the grid. Blue areas symbolize regions with decreased voltages—by applying the unintended reactive power flow—whereas red regions describe increased voltages.

Fig. 5 visualizes the voltage distribution on all nodes in a low voltage grid with three local network areas. The black points represent the grid nodes. The grid is posed in the correct position. The annotation of the axes describes the geographical extent of the grid. The area in the northwest shows slightly decreased voltages of approximately 0.2 V. By means of the changing colors the borders of the local network areas are clearly visible. The medium network area shows decreased voltages up to 0.4 V, whereas the southeast network area reveals slightly increased voltages. This fits quite

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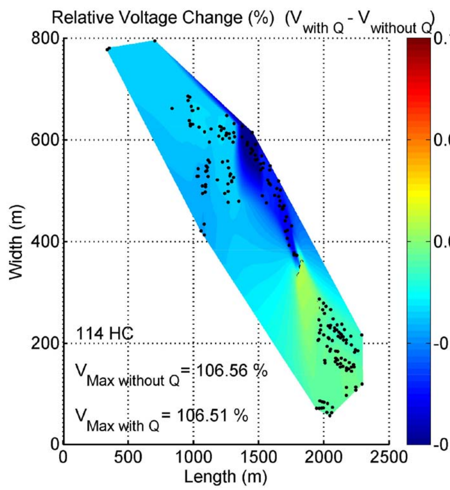

Fig. 5. Comparison of the grid voltage by the simulation method C1—mean during the maximum PV feed-in with and without the unintended reactive power flow of PV inverters for the low voltage grid with 114 HCs.

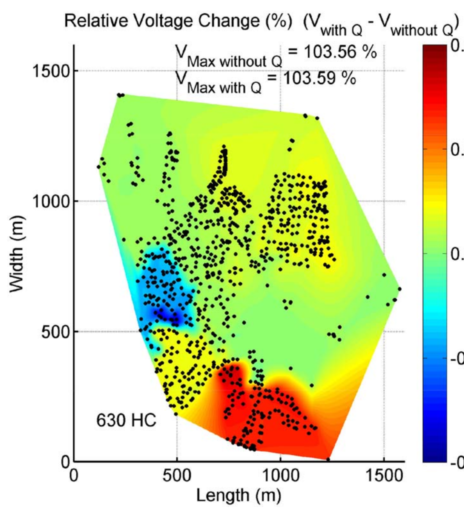

Fig. 6. Comparison of the grid voltage by the simulation method C1—mean during the maximum PV feed-in with and without the unintended reactive power flow of PV inverters for the low voltage grid with 630 HCs.

well with Fig. 2. The mean voltage is reduced by applying the unintended reactive power flow, but there are still nodes with enhanced voltages due to the capacitive behavior of some inverters. The node with the maximum voltage in the whole low voltage grid lies in an inductive network area. Hence, by applying the unintended reactive power flow, the voltage is decreased. All unintended reactive power flow sums up to 25.2 kVAr. This is a share of 3.6% of the installed PV inverter power.

The low voltage grid in Fig. 6 again displays local network areas with increased and decreased grid voltages. As shown in Fig. 3, there is one inverter with a strong inductive behavior. This inverter reduces the voltage in the blue colored network area. The borders of this network area are clearly visible. The area in the southeast from the blue one depicts a slight voltage rise. This is the area where the node with the maximum voltage is located. Therefore, this voltage is increased by applying the unintended reactive power flow.

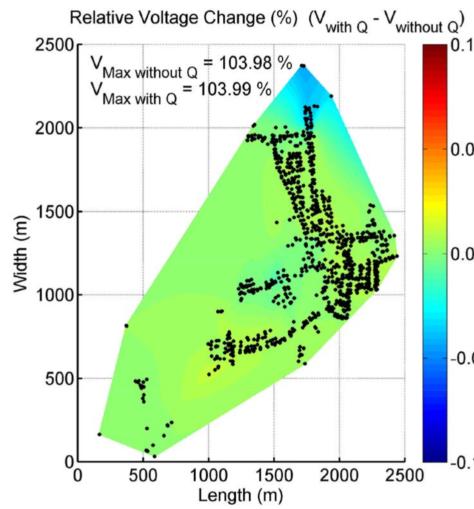

Fig. 7. Comparison of the grid voltage by the simulation method C1—mean during the maximum PV feed-in with and without the unintended reactive power flow of PV inverters for the low voltage grid with 430 HCs.

The highest voltage rise occurs in the southernmost network area and amounts to 0.5 V. In the red marked zone of Fig. 6, the cyan-colored inverter of Fig. 3 is installed. This inverter shows a capacitive behavior in full load operation and therefore a voltage boosting effect. The voltages in the other local network areas remain nearly constant. A total of 35.4 kVAr occurs in this low voltage grid and accounts for 5.3% of the nominal inverter power.

In the low voltage grid in Fig. 7, almost no voltage changes are visible due to the fact that in total 14.4 kVAr and a share of 1.8% of the nominal power occur. This is much less than the other two low voltage grids reveal.

The differences in the color for the three low voltage grids are better and worse performing inverters. The installed inverters of the low-voltage grid according to Fig. 7 shows a quite preferable performance (Fig. 4) with low deviations of the reactive power from the specification. In the other low voltage grids are installed inverters with a significantly worse performance (Figs. 2 and 3). These inverters do have an influence on all nonmeasured inverters and therefore an intense effect on the grid voltage (Figs. 5 and 6).

In summary, all three low voltage grids have an inductive overall attitude. Nevertheless, the voltage ranges are quite different. Table I exposes a recap of the maximum voltage with and without the unintended reactive power flow for each distribution grid. The influence of the voltage depends strongly on distribution of the different PV inverters. An inductive overall behavior of a low voltage grid does not automatically mean that the maximum voltage of this grid is reduced, as shown in Fig. 6. Nevertheless, the absolute values of voltage changes due to unintended reactive power of PV inverters with a power factor specification of one are insignificant.

The simulation methods C2—ind and C3—cap are worst case scenarios in the mean with the highest deviations from the power factor specification. Table I displays the results of the maximum voltages for the three analyzed low voltage grids. For scenario C2—ind, the voltage reduction to 101.83% in the second distribution grid is quite large due to the one strong

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TABLE I
MAXIMUM NOMINAL GRID VOLTAGES IN % WITH AND WITHOUT UNINTENDED REACTIVE POWER FOR EACH LOW VOLTAGE GRID FOR THE THREE SIMULATION VARIANTS

	Distribution Grid One	
	Without Q	With Q
$V_{C1-Mean}$ (%)	106.56	106.51
V_{C2-Ind} (%)	106.56	106.00
V_{C3-Cap} (%)	106.56	106.76
	Distribution Grid Two	
	Without Q	With Q
$V_{C1-Mean}$ (%)	103.56	103.59
V_{C2-Ind} (%)	103.56	101.83
V_{C3-Cap} (%)	103.56	103.71
	Distribution Grid Three	
	Without Q	With Q
$V_{C1-Mean}$ (%)	103.98	103.99
V_{C2-Ind} (%)	103.98	103.95
V_{C3-Cap} (%)	103.98	103.99

inductive inverter (Fig. 3) and the impact of this inverter on all the nonmeasured PV systems. This system leads to a reactive power exchange with the grid of more than half of the active feed-in. In the third distribution grid, the maximum inductive and capacitive powers are much lower than the first and second distribution grids. This explains why the voltage changes among the three different simulation methods are marginal.

C. Influences on Power Loss in the Grid

The influence of the unintended reactive power flow on the grid power losses are shown in Figs. 8 and 9. For a worst case estimation, the simulation method C2—ind (Fig. 8) and C1—mean (Fig. 9) for the second low voltage grid according to Figs. 3 and 6 are taken into account and described in this section. The results of the calculation according to method C3—cap are between the results of C1—mean and C2—ind. The distribution grid operator and, therefore, the general public pay for these losses. In the following discussion, the term "loss" refers to the dissipation power. Again all simulations are done with and without the unintended reactive power flow of PV inverters with a power factor specification of one.

The first row of Fig. 8 shows the results of cable and transformer losses without the unintended reactive power of PV inverters. Therefore, the bar chart displays the probability density of the losses over one complete year of investigation (2011). The mean value of all losses in the complete medium voltage grid (total feed-in of all low voltage grids connected to this medium voltage grid except the analyzed one: 19.33 MVA) sums to 113.35 kW. The maximum value occurred on a sunny spring day and is as high as 121.93 kW. During the majority (55%) of the investigation period the losses are around 112 kW. This is the case if no PV feed-in arises (loads are constant). The highest losses of more than 120 kW are obtained on clear sky early-summer days.

The second row of Fig. 8 displays the cable and transformer losses with the unintended reactive power flow of PV inverters.

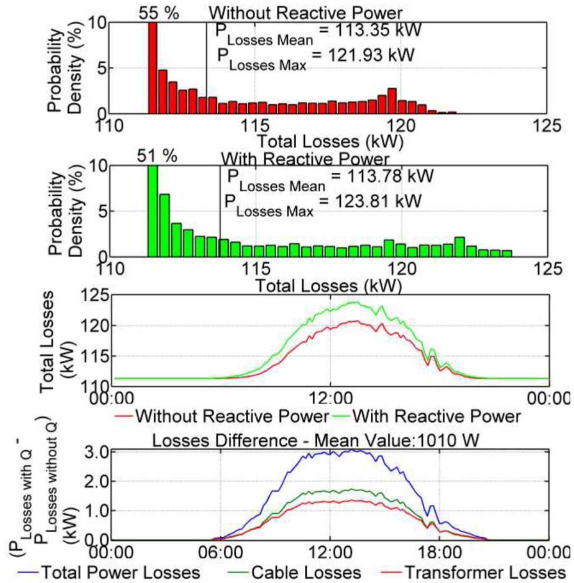

Fig. 8. Comparison of grid loss with and without the unintended reactive power flow of PV inverters. The average and also the maximum loss are higher by applying the reactive power flow to the simulation. Simulation method C2—ind is displayed.

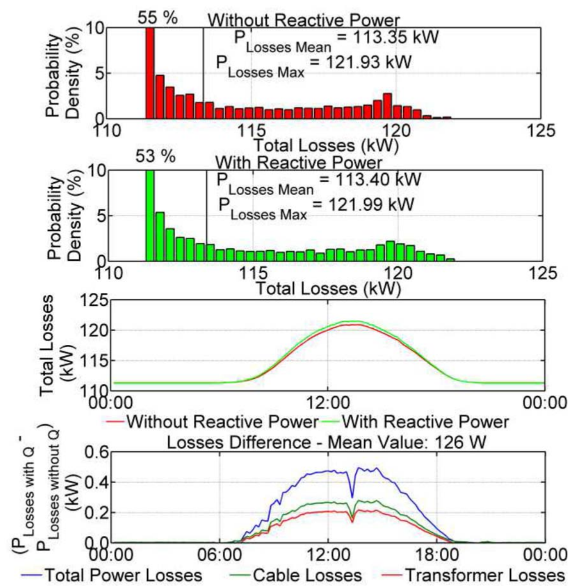

Fig. 9. Comparison of grid loss with and without the unintended reactive power flow of PV inverters. The average and also the maximum loss are higher by applying the reactive power flow to the simulation. Simulation method C1—mean is displayed.

The maximum loss increases to 123.81 kW and is around 1.9 kW higher than without reactive power. The medium value amounts to 113.78 kW. This value is also around 0.4 kW higher than without reactive power. The minimal losses are slightly reduced compared to the losses without reactive power. These losses arise during the night because of the high capacitive power flow of the LCL grid filters of some inverters and the inductive loads. Consequently, a compensation of reactive power takes place.

The green graph of the third row shows the profiles of the day (May 9, 2011), with the highest power flow and, therefore,

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the highest loss with reactive power. The red graph is the profile of the loss on the same day without reactive power, but not the profile with the highest loss by neglecting reactive power flow. There is almost constant loss during the night of around 112 kW in the whole medium voltage grid.

The elevated loss during the daytime is a result of the feed-in in the investigated low voltage grid, due to the fact that the load and supply in all other connected low voltage grids are constant over the entire simulation period. Hence, this low voltage grid causes additional maximum loss because of the high active power feed-in of around 9 kW or 1.3% of the installed PV capacity. This means the maximum power loss on this specific day without reactive power is 121 kW.

The maximum PV feed-in power amounts to 85% of the systems rated power. This is based on earlier investigations in the research project and on [14] and [15]. This means the maximum PV feed-in accumulates to around 570 kW in this low voltage grid and the loss is 1.6% of the PV feed-in.

By applying the reactive power flow, the maximum loss increases to almost 124 kW and is approximately 3 kW higher than without reactive power. This implies that approximately 0.5% of the active PV feed-in is lost because of the additional reactive power flow. The energy lost due to the reactive power flow amounts to 22 kWh on this day. In contrast, the total active feed-in energy on this day in this specific low voltage grid amounts to 4827 kWh. This suggests that approximately 0.45% of the produced energy is lost due to the unintended reactive power flow. The total loss caused by the unintended reactive power flow over the entire year under investigation is summed to 2598 kWh. This is more than half of the energy that is produced on the most profitable day.

In the last row of Fig. 8, the difference between the loss with reactive power and without reactive power over the day with the highest power flow and, therefore, the highest loss is exhibited. The red graph illustrates the difference in transformer loss with a maximum around 1.3 kW. The green curve illustrates the loss difference on all cables of the distribution grid. This maximum amounts to approximately 1.7 kW. To sum it up, the additional loss of maximal 3 kW due to the unintended reactive power flow is a result of additional transformer and cable loss, whereby the supplementary cable loss is higher than the transformer loss.

By applying the reactive power according to the simulation method C1—mean (Fig. 9), the maximum and also medium loss of the distribution grid, compared to C2—ind, are reduced. The maximum loss of the complete medium voltage grid and subordinate low voltage grid amounts to 121.99 kW. This value is 1.8 kW lower than in the C2—ind scenario and only marginally higher than without reactive power flow. The additional maximal cable and transformer losses are in the range of 200–300 W. Again, the additional cable loss is higher than the additional transformer loss.

The energy that is lost due to the supplementary unintended reactive power flow on the day with the highest power flow amounts to 3.8 kWh. The energy that is lost over the whole year of investigation aggregates to 453 kWh. This means the energy lost because of unintended reactive power flow is 10% of the energy produced on the most profitable day.

Nevertheless, losses in the grid are increased by applying the unintended reactive power flow of PV inverters with a power factor specification of one into the simulation. Also, the utilization rates of the cables and transformers are increased. This means that the actual utilization rates are higher than those simulated with conventional methods; and earlier, respectively, higher, grid enforcement is necessary to prevent overload.

IV. Results

Most of the PV inverters installed nowadays are inverters with a power factor specification of one. This means that no reactive power—but only pure active power—should be fed into the grids. Various observations have shown a dispersion of the active and apparent power feed-in and, thus, a reactive power flow. This paper evaluates the influence of the unintended reactive behavior of PV inverters with a fixed power factor specification of one on distribution grids.

The unintended reactive power flow of most of the analyzed inverters confirms linear dependence on active power. Therefore, a reactive power best-fit polynomial of the first degree for each inverter is developed. The application of this polynomial to each inverter in voltage and load flow simulations lead to more precise results of the real system conditions.

Simulation of the grid voltage shows an inductive overall attitude of PV inverters in three exemplary low voltage grids. Nevertheless, the voltage ranges are quite different. The influence of unintended reactive power on the voltage depends strongly on distribution of the different PV inverters. An inductive overall behavior of a low voltage grid does not automatically mean that the maximum voltage of this grid is reduced. On the contrary, these simulations show an even bigger voltage spread in the distribution grids due to the unintended reactive power flow. In general, grid conditions of low voltage grids are not known by the grid operators. Distribution network operators simulate the grids to figure out grid conditions and to make sure that all grid parameters are within an allowed range. For all PV systems, including an installed inverter with a power factor specification of one, only active power values are applied. Hence, the real voltages deviate from the simulated voltages.

Losses in the grid are slightly increased by applying the unintended reactive power flow of PV inverters with a power factor specification of one into the simulation. The utilization rate of the cables and transformers is increased. This means that the real utilization rates are higher than the simulated ones.

V. Conclusion

The primary question of this paper was, if the influence of unintended reactive power flow has to be considered in grid planning and power system management in smart grids.

The answer to that question reads as follows.

1) Under normal operating conditions the reactive power flow of PV inverters with a power factor specification of one is not relevant for grid operation and grid planning. The results of this paper show an inductive behavior of the inverters with the highest deviation from the power factor specification in full load operation. This means

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that even if a larger number of inverters—that do not fulfill their power factor specifications—is installed, no grid disturbance with voltages that are too high will be expected. The grid voltage, rather, will be decreased. Also, the influence on grid power loss is marginal.

2) Nevertheless, if voltage or overload problems are not explainable by the active power flow and intended reactive power flow, they can be a result of the unintended reactive power flow and their influence on grid voltage and grid loss. Those grid regions have to be analyzed by applying the unintended reactive power flow of PV inverters with a power factor specification of one. This approach can help network operators locate and understand the reasons for grid problems.

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